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(54) Reduction of interference in duplex discrete multitone communications systems

(57) An Asymmetric Digital Subscriber Loop (ADSL) Discrete Multi-Tone system has disjoint and adjacent upstream and downstream channels. During the training phase of an ADSL connection, an ADSL DMT transmitter first determines a round trip propagation delay by transmitting a ranging signal to a far-end ADSL endpoint. During the subsequent communications phase, the ADSL transmitter synchronizes transmission of DMT symbols to a reference clock. In addition, the cyclic extensions of each DMT symbol are increased as a function of the propagation delay.

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signal is generated using an inverse fast Fourier transform of a size equal to the number of carriers in the signal.)

[0008] In an embodiment of the invention, an ADSL DMT system has disjoint and adjacent upstream and downstream channels. During the training phase of an ADSL connection, an ADSL DMT transmitter first determines a round trip propagation delay by transmitting a ranging signal to a far-end ADSL endpoint. During the subsequent communications phase, the ADSL transmitter synchronizes transmission of DMT symbols to a reference clock. In addition, the cyclic extensions of each DMT symbol are increased as a function of the propagation delay.

[0009] In a second embodiment of the invention, an ADSL DMT system has an upstream and downstream channel that partially overlap. During the training phase of an ADSL connection, an ADSL DMT transmitter first determines a round trip propagation delay by transmitting a ranging signal to a far-end ADSL endpoint. During the subsequent communications phase, the ADSL transmitter synchronizes transmission of DMT symbols to a reference clock. In addition, the cyclic extensions of each DMT symbol are increased as a function of the propagation delay. An ADSL receiver includes a single tap echo canceler for each carrier in that portion of bandwidth where the upstream and downstream channels overlap.

Brief Description of the Drawing

[0010]

FIG. 1 conceptually illustrates cyclic extension as used in ADSL DMT transmission to compensate for ISI;
FIG. 2 illustrates prior art ADSL communications equipment;
FIG. 3 shows an illustrative ADSL bandwidth allocation;
FIG. 4 shows an illustrative CE gate detector element of CE gate 160 of FIG. 2;
FIG. 5 illustrates another representation of prior art ADSL communications equipment;
FIGs. 6 and 7 conceptually illustrate a form of interference in ADSL communications;
FIGs. 8 - 10 illustrate the inventive concept;
FIG. 11 shows an ADSL communications system in accordance with the principles of the invention;
FIG. 12 shows ADSL equipment in accordance with the principles of the invention for use in the system of FIG. 11;
FIG. 13 shows an illustrative flow chart embodying the principles of the invention for use in the ADSL equipment of FIG. 12; and
FIG. 14 shows ADSL equipment in accordance with the principles of the invention for use in the system of FIG. 11.

Detailed Description

[0011] Before describing the inventive concept, prior art ADSL communications equipment 100, shown in FIG. 2, is described in order to provide some background information. The elements shown in FIG. 2 are well-known and will not be described in detail. For the purposes of description, it is assumed that ADSL equipment 100 is located at the CO. The corresponding ADSL equipment located at the subscriber's premise, i.e., the far-end ADSL equipment, or CPE, is similar and will not be described herein. It is assumed that ADSL equipment 100 conforms to ANSI T1.413. Also, it is assumed the ADSL system represented by FIG. 2 allocates bandwidth as shown in FIG. 3. The POTS channel is in the 0 to 4 Khz range, the upstream channel, i.e., from the CPE to the CO, is in the 25 Khz to 138 Khz; while the downstream channel, from the CO to the CPE, is in the 138 Khz to 1.1 Mhz range. As such, the upstream channel and downstream channel are disjoint and also adjacent.

[0012] Returning to FIG. 2, the transmitter portion of ADSL equipment 100 comprises serial-to-parallel converter (S/P) 105, symbol mappers 110, inverse fast Fourier transform element (IFFT) 115, cyclic extender (CE) 120, parallel-to-serial converter (P/S) 125, digital-to-analog converter (D/A) 130, and hybrid 135. A data signal is applied to S/P 105, which converts the data signal from serial to parallel form and provides 256 signals n_0 through n_{255}. Signals n_0 through n_{255} are applied to symbol mappers 110. The latter comprises 256 symbol mappers, one for each of the parallel output signals of S/P 105. (As described further below, the number of bits encoded by each symbol mapper, and hence the number of bits S/P 125 provides in each n_i is determined as a result of a spectral response determined during a training phase.) The resulting 256 output symbol streams from symbol mappers 110 are complex valued and are applied to IFFT 115, which modulates the various different carriers with the output symbol stream to provide 512 output signals. (IFFT 115 takes the complex conjugate (not shown) of the 256 output symbol streams to provide 512 real signals.) The 512 output signals from IFFT 115 are applied to CE 120, which performs the above-mentioned cyclic extension. These extended signals are then applied to P/S 125 to provide a serial output signal, the DMT symbol plus cyclic extender, that is converted from digital to analog by A/D 130. The latter provides a downstream ADSL signal representing a sequence of extended DMT symbols, to hybrid 135, which couples this downstream ADSL signal to combiner/splitter 150, which adds in the POTS channel. The output signal from combiner/splitter 150 comprises the POTS channel in the 0 to 4 Khz range and the downstream signal in the 138 Khz to 1.1 Mhz range and is applied to the communications

appear in the upstream direction notwithstanding the use of disjoint frequency bands. (A similar effect is possible for the far-end ADSL endpoint with respect to upstream transmissions leaking into the downstream signal.) In particular, in order to recover DMT symbol C_u, the processing performed by DMT Demodulator 195 spans a period of time represented by dotted bracket 2, which includes both DMT symbol A_d, DMT symbol B_d, and the above-mentioned discontinuity. (With respect to the downstream signal shown on FIG. 6, it should be remembered that although shown as two separate cyclic extensions CE_1 and CE_2 for the purposes of this explanation, in practice a single cyclic extension CE is added by the transmitter, where $CE = CE_1 + CE_2$. A similar comment is applicable for the downstream signal in FIGs. 7 - 10.)

[0020] In comparison, FIG. 7 illustrates the case when there is no discontinuity between consecutive DMT symbols. In FIG. 7, in the downstream direction the same DMT symbol A_d is consecutively transmitted by, e.g., DMT modulator 185 of FIG. 5. In the upstream direction, and in the period of time that DMT modulator 185 is transmitting DMT symbols A_d, DMT symbol C_u is received at hybrid 135. The latter provides received upstream DMT symbol C_u, and a portion of the downstream transmission due to leakage, to DMT demodulator 195. Now, as can be seen by reference to the dotted bracket 2 of FIG. 7, this leakage only includes the carriers represented by DMT symbol A_d and, therefore, there is no discontinuity as between the consecutive downstream DMT symbols. Since these downstream carriers are disjoint in frequency from the upstream carriers, there is no effect on the received upstream transmission.

[0021] One method of removing the above-described interference is to use a filter in the receiver, e.g., a low pass filter (LPF) for ADSL equipment that is receiving the upstream signal. Unfortunately, this filtering may significantly increase the effect of envelope delay distortion on the received ADSL signal and thus the value of the cyclic extension.

[0022] However, we have realized that synchronization of DMT symbol transmissions also reduces this interference. Therefore, and in accordance with the invention, an ADSL transmitter is synchronized with a far-end ADSL transmitter. Additionally, we have realized that such synchronization simplifies the design of an echo canceler, which can be used in ADSL systems where the upstream channel and downstream channel overlap.

[0023] The inventive concept is shown in FIGs. 8 - 10. The latter are explained in the context of ADSL equipment located in the CO. A similar description applies to the ADSL CPE and is not described herein. The effect of synchronization of ADSL transmitters assuming zero, or negligible, propagation delay is shown in FIG. 8. In the downstream direction different DMT symbols A_d and B_d are consecutively transmitted by the ADSL CO equipment. At the same time, and in the upstream direction, the ADSL CO equipment receives DMT symbols C_u and D_u. Although there is leakage through the hybrid of the ADSL CO equipment of the downstream transmission signal, the processing for each received DMT symbol only spans a single downstream DMT symbol as can be seen by the dotted brackets 2.

[0024] In comparison, FIG. 9 shows the effect of a noticeable upstream propagation delay, t_{pu}. It can be observed from FIG. 9 that the upstream propagation delay, for some values, can still cause an ADSL received DMT symbol to be affected by more than one transmitted DMT symbol via leakage. (This is shown by dotted brackets 2 of FIG. 9.) Therefore, and in accordance with the principles of the invention, for some ADSL systems the cyclic extension is increased in value as a function of the propagation delay of the ADSL system to maintain synchronization. This additional cyclic extension delay can be added in a number of different ways.

[0025] One method is simply to add a fixed amount of cyclic extension independent of the propagation delay.

[0026] Another method is shown in FIG. 10, where each cyclic extension is now equal to:

$$CE_{t1} = CE_1 + \alpha\ t_{pu}, \tag{1}$$

and

$$CE_{t2} = CE_2 + (1-\alpha)t_{pu}, \tag{2}$$

where CE_{t1} and CE_{t2} are the new values for each cyclic extension taking into account a time delay, denoted by the subscript t, CE_1 and CE_2 are the values of the respective original cyclic extension used to compensate for the above-mentioned ISI interference, and t_{pu} is a measured value of the upstream propagation delay denoted by the subscript pu. FIG. 10 illustratively shows a value of $\alpha = .5$. Consequently, from FIG. 10, the total cyclic extension value is

$$\textit{total cyclic extension value} = CE_1 + CE_2 + t_{pu}. \tag{3}$$

[0027] In general, in this approach, the round trip delay is used to determine the new value for the total cyclic extension, CE_T, with respect to a propagation delay in accordance with the principles of the invention, where,

synchronization. In these systems, a number of alternative are possible.

[0036] One alternative is to increase the value of the cyclic extension as noted above. In one method of doing this, controller 390 provides a value for the CE_T, described above, to both DMT modulator 385 and DMT demodulator 395, via signaling 392 and 391, respectively. DMT modulator 385 modifies its respective cyclic extension element (not shown) to generate cyclic extensions having an additional duration of CE_T. Although provided to DMT demodulator 395 for the sake of completeness, the CE gate element does not require to know how the cyclic extender is partitioned. As noted above, the CE gate element extracts the DMT symbol using the best 512 samples within a received extended DMT symbol. Once the DMT symbol is extracted, the remaining portions of the extended DMT symbol are, by definition, the cyclic extender (prefix and postfix).

[0037] In one variation of this approach, controller 390 provides a fixed value for CE_T to DMT modulator 385 and DMT demodulator 395 via signals 391 and 392.

[0038] In another variation of this approach, the value for CE_T is determined during the above-mentioned training phase of an ADSL connection. While the value for CE_T is the same in either ADSL equipment located at the CO or the CP, controller 390 generates this value differently depending on whether or not controller 390 is located in the CO or the CP. In the case when ADSL equipment 300 is located in the CO, controller 390 transmits, during training, a ranging signal (simply a predefined signal known to the far-end ADSL equipment). Upon receipt, the far-end ADSL equipment retransmits the ranging signal back to ADSL equipment 300. (Ranging techniques are known in the art and others may also be used.) Upon receipt of the ranging signal, controller 390 calculates the round trip propagation delay and determines a value for CE_T. (This calculated delay assumes negligible processing delay in the far-end ADSL equipment. If this processing delay is significant, the measured value in controller 390 must be adjusted for this processing delay.) Once calculated, this value of CE_T is also transmitted to the far-end ADSL equipment for its use. (This is similar to the above-mentioned transmission of the bit-loading table). Other techniques could also be used, e.g., the ADSL located at the CP can generate the ranging signal, etc. (It should be realized, that those embodiments in which ADSL equipment 300 is located in the CP have already been described, i.e., in this case ADSL equipment 300 is the far-end ADSL, as described above.)

[0039] As noted above, in some situations, these propagation delays may not be equal, and increasing the value of the cyclic extensions may not be enough to maintain synchronization. In these situations, controller 390 additionally delays sync signal 393 by δt, from equation (6).

[0040] Another equivalent alternative is for controller 390 to control DMT modulator 385, e.g., by turning it on and off. In this case, controller 390 uses sync signal 393 to turn on, and off, DMT modulator 385. Here, sync signal 393 is a function of CL 394 and, if used, the increased cyclic extender value (whether fixed or as a function of a propagation delay). The latter generates the same effect as increasing the value of the cyclic extension. In this case, signal 392 is not necessary.

[0041] It should be noted that this additional signaling, CL signal 394, sync 393, etc., is shown to highlight the inventive concept. However, signaling 196 and 197 can also be suitably modified in accordance with the inventive concept.

[0042] As noted above, in some cases, synchronization of the DMT symbols by use of the recovered symbol clock from the CE gate element is enough to provide DMT symbol synchronization in the ADSL system. In the worst case, a cyclic extension value must be increased (or equivalently increased). One such method is shown in FIG. 13. The latter shows an illustrative method in accordance with the principles of the invention for use in ADSL equipment, e.g., in controller 390 of FIG. 12. In step 600, controller 390 determines the round trip delay as described above. (As described above, the actual steps will vary depending on which end of the ADSL connection transmits the ranging signal.) In step 605, controller 390 adjusts the value of the cyclic extension as a function of the round trip delay and provides this value, CE_T, to both modulator 385 and demodulator 395. In step 610, controller 390 provides a synchronization, or sync, signal to DMT modulator 385. (It should be noted that ADSL equipment can dynamically determine when to use the method illustrated in FIG. 13 as, e.g., a function of the above-measured spectral response. If the results of this measurement are within a particular range, or over, or under a particular value, then performing the above-described method.)

[0043] As noted above, in the instance when the downstream channel partially overlaps the upstream channel, echo cancellation is required. Typically, this echo cancellation is complex and, as a result, costly. However, and in accordance with the principles of the invention, an ADSL endpoint that is synchronized with an opposite ADSL endpoint can use a simpler — and cheaper — echo canceler. An illustrative ADSL equipment 400 is shown in FIG. 14.

[0044] In this embodiment of the invention, an ADSL DMT system has an upstream and downstream channel that partially overlap, e.g., the downstream channel can completely overlap the upstream channel. In this latter example, the downstream channel extends from 25 Khz to 1.1 Mhz. ADSL equipment 400 functions in a similar fashion to ADSL equipment 300 with respect to synchronization and modification of the cyclic extension as a function of round trip delay. In addition, ADSL equipment 400 includes a single tap echo canceler for each carrier in that portion of bandwidth where the upstream and downstream channels overlap.

[0045] The single tap echo canceler is represented by single tap adaptive filter 410, and combiner 405. Combiner

9. The method of claim 1 wherein the synchronizing step includes the steps of:

performing clock recovery on the received multi-carrier signal for recovery of a timing signal; and
using the recovered timing signal to synchronize transmission.

10. The method of claim 9 wherein the recovered timing signal is an DMT symbol clock.

11. The method of claim 1 wherein the multi-carrier equipment is asynchronous digital subscriber line (ADSL) equipment.

12. The method of claim 1 wherein the synchronization step turns on and off the transmitter to perform the synchronization.

13. Apparatus comprising:

a discrete multi-tone (DMT) modulator for transmitting a sequence of extended DMT symbols to a far-end multi-carrier endpoint;
a DMT demodulator for receiving a sequence of extended DMT symbols from the far-end multi-carrier endpoint; and
a controller for synchronizing the DMT modulator to the received sequence of extended DMT symbols.

14. The apparatus of claim 55 wherein each extended DMT symbol comprises a cyclic extender and a DMT symbol, and the controller synchronizes the DMT modulator such that a received DMT symbol and a transmitted extended DMT symbol overlap one another in time.

15. The apparatus of claim 55 wherein the controller further adjusts the value of the cyclic extender as a function of a propagation delay.

16. The apparatus of claim 57 wherein the propagation delay is equal to a round trip delay between the apparatus and the far-end ADSL endpoint.

17. The apparatus of claim 55 wherein the controller further adjusts the value of the cyclic extender by a fixed amount for maintaining synchronization.

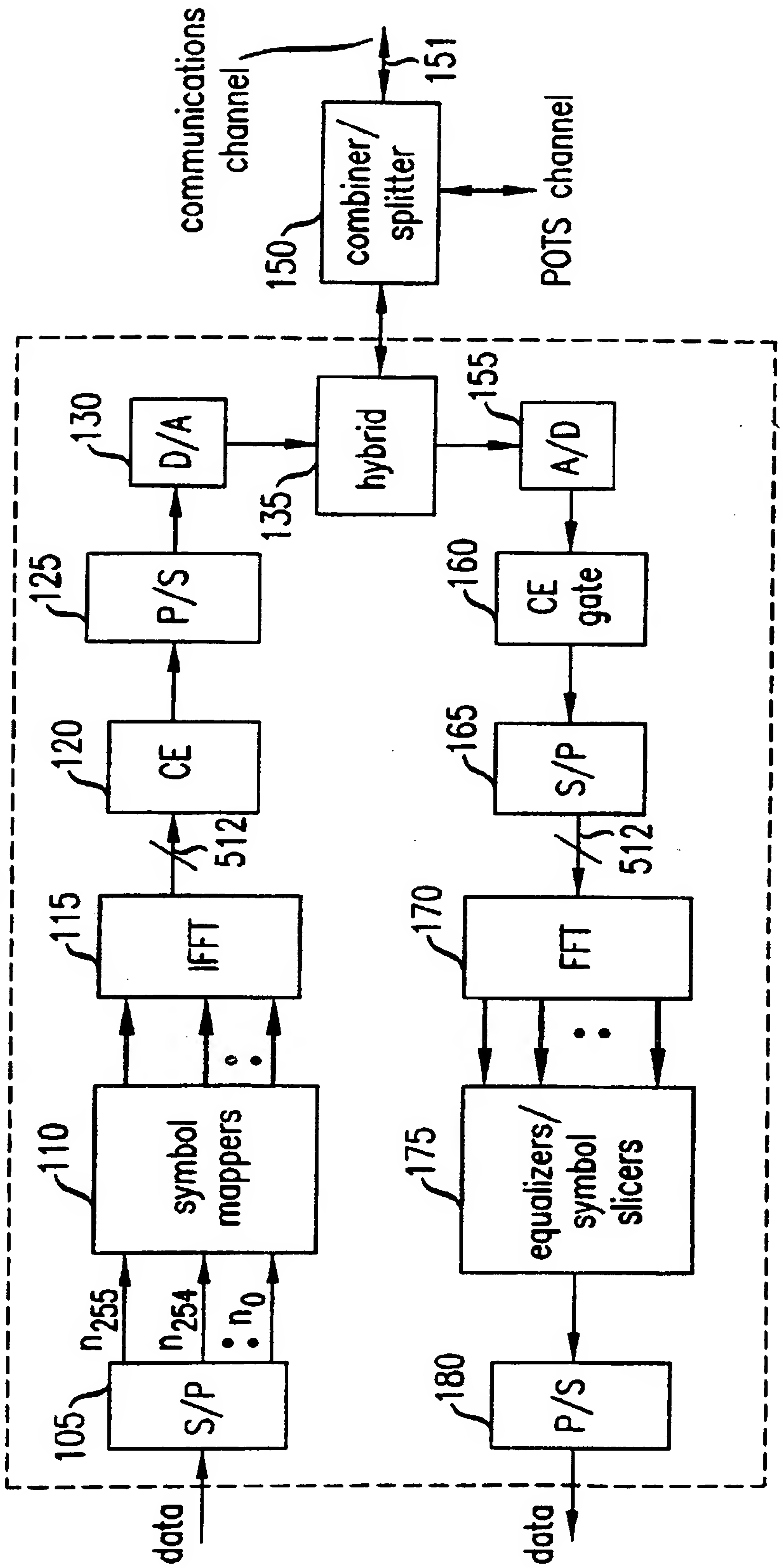
18. The apparatus of claim 55 wherein the DMT demodulator provides a timing signal recovered from the received sequence of extended DMT symbols and wherein the controller uses the recovered timing signal to synchronize transmission.

19. The apparatus of claim 60 wherein the recovered timing signal is a DMT symbol clock.

20. The apparatus of claim 55 wherein the multi-carrier signal is an asynchronous digital subscriber line (ADSL) DMT signal.

21. The apparatus of claim 55 wherein the controller synchronizes the DMT modulator by turning it on and off.

FIG. 2
(PRIOR ART)
100



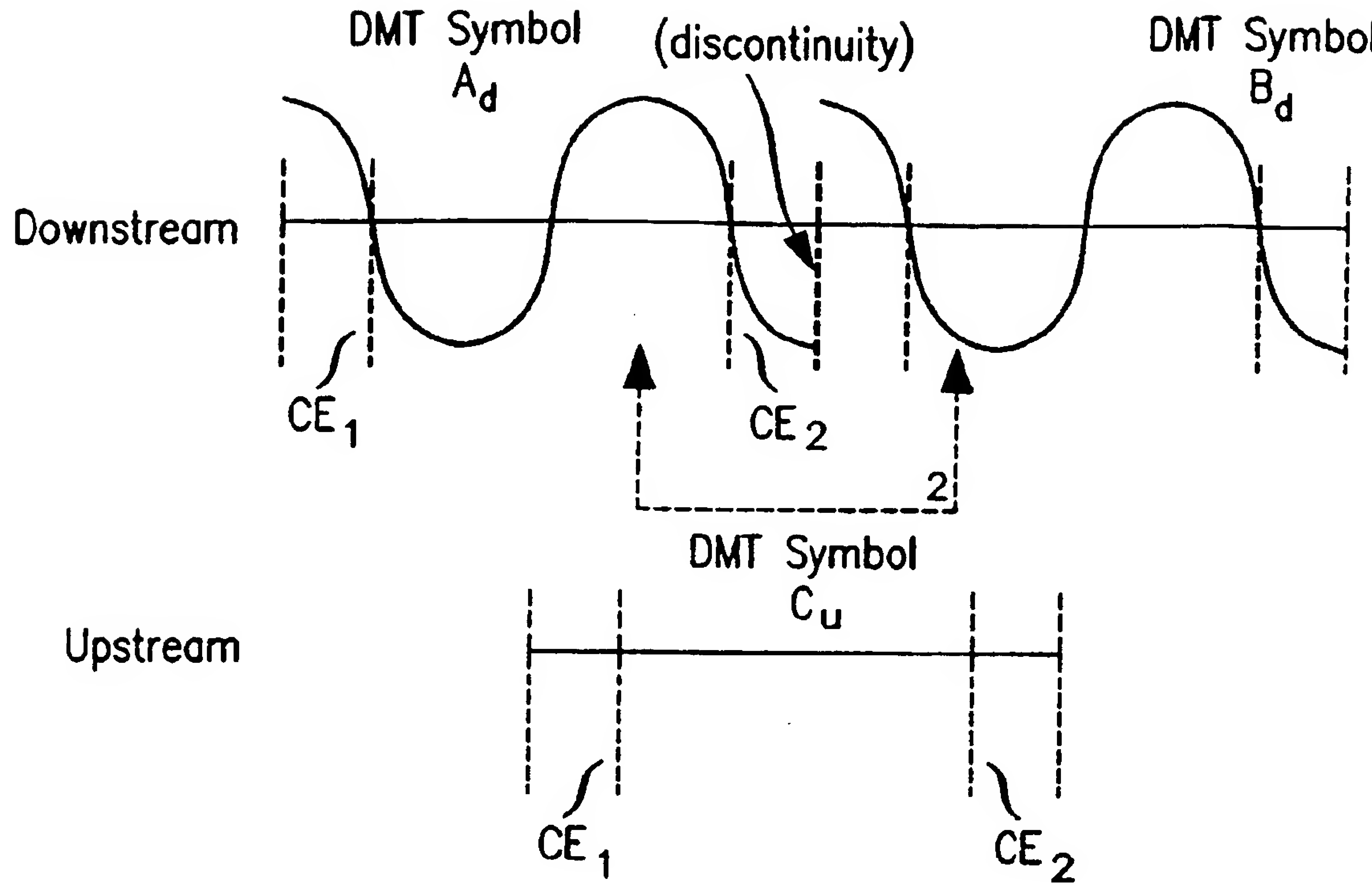

DMT Symbol
A_d
(discontinuity)
DMT Symbol
B_d
Downstream
CE_1
CE_2
2
DMT Symbol
C_u
Upstream
CE_1
CE_2

FIG. 6

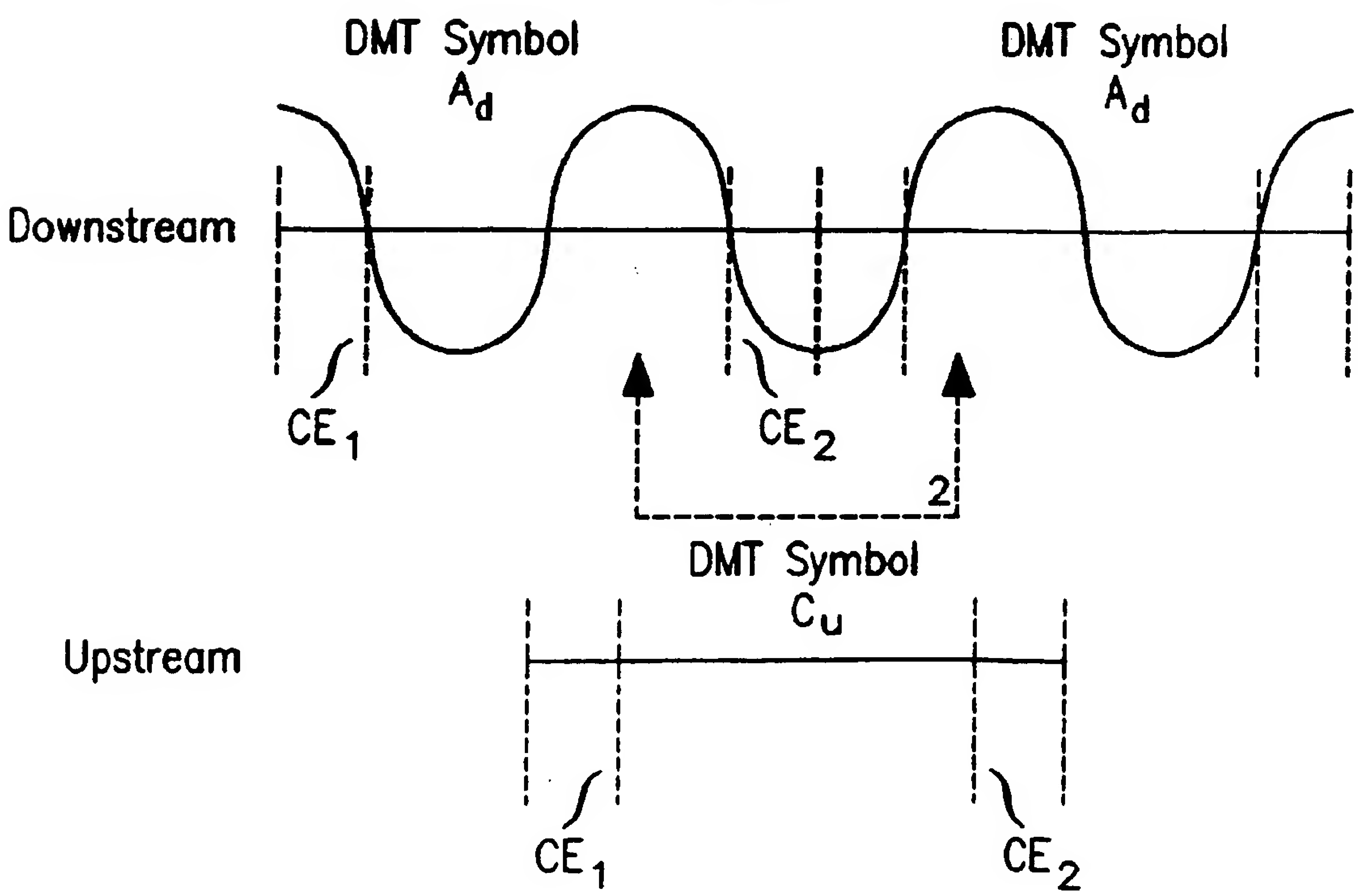

DMT Symbol
A_d
DMT Symbol
A_d
Downstream
CE_1
CE_2
2
DMT Symbol
C_u
Upstream
CE_1
CE_2

FIG. 7

FIG. 10

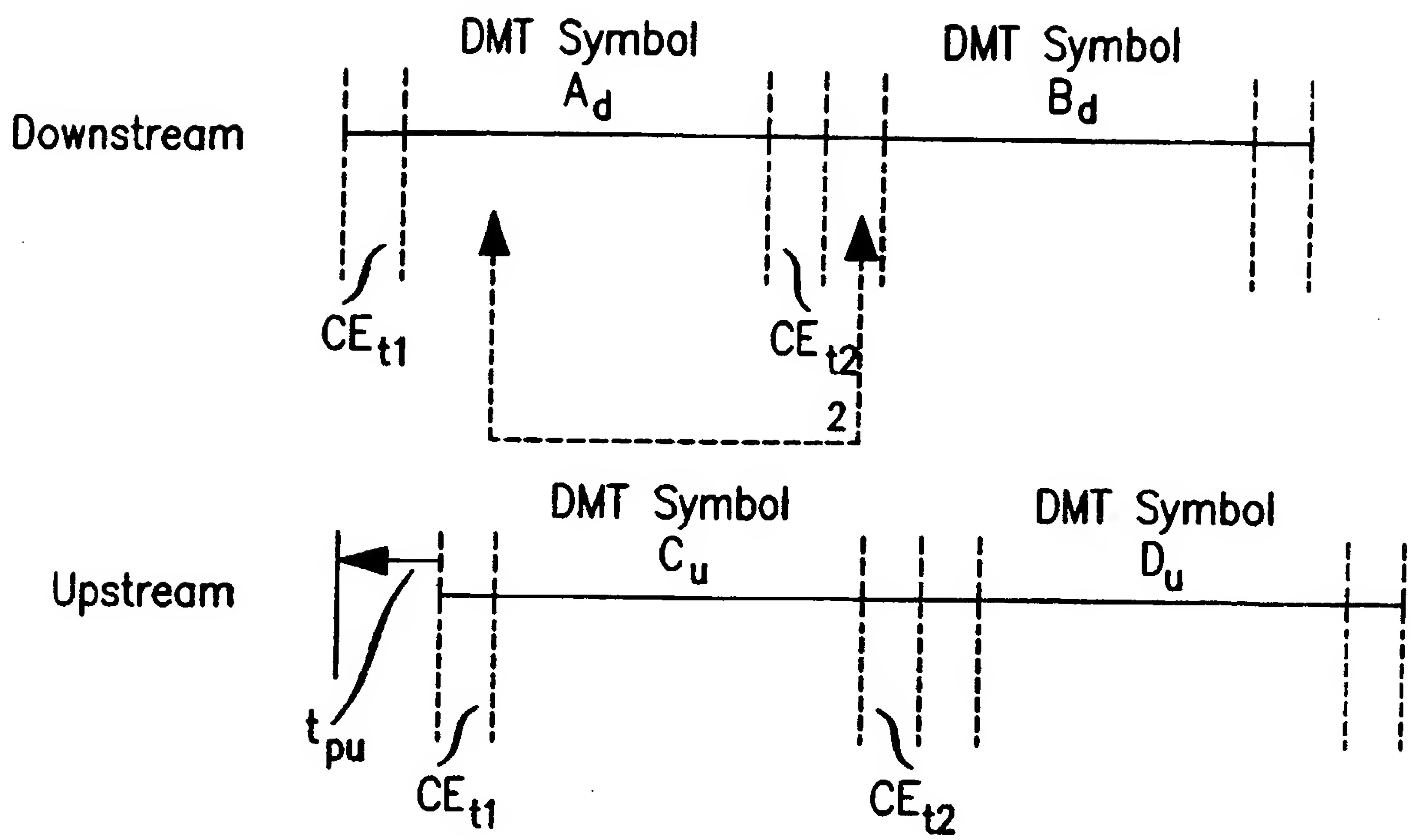

DMT Symbol
A_d
DMT Symbol
B_d
Downstream
CE_{t1}
CE_{t2}
2
DMT Symbol
C_u
DMT Symbol
D_u
Upstream
t_{pu}
CE_{t1}
CE_{t2}

FIG. 11

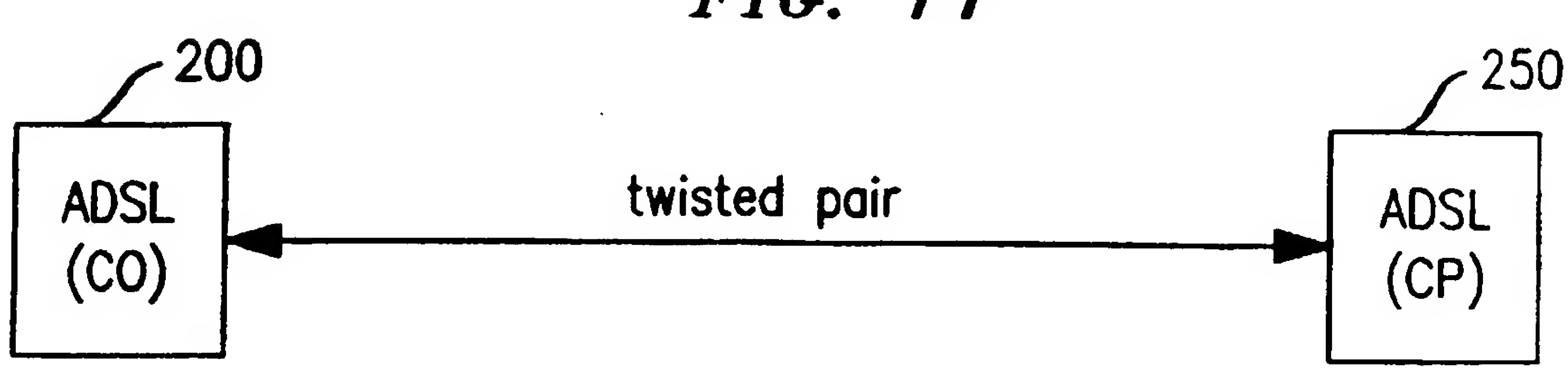
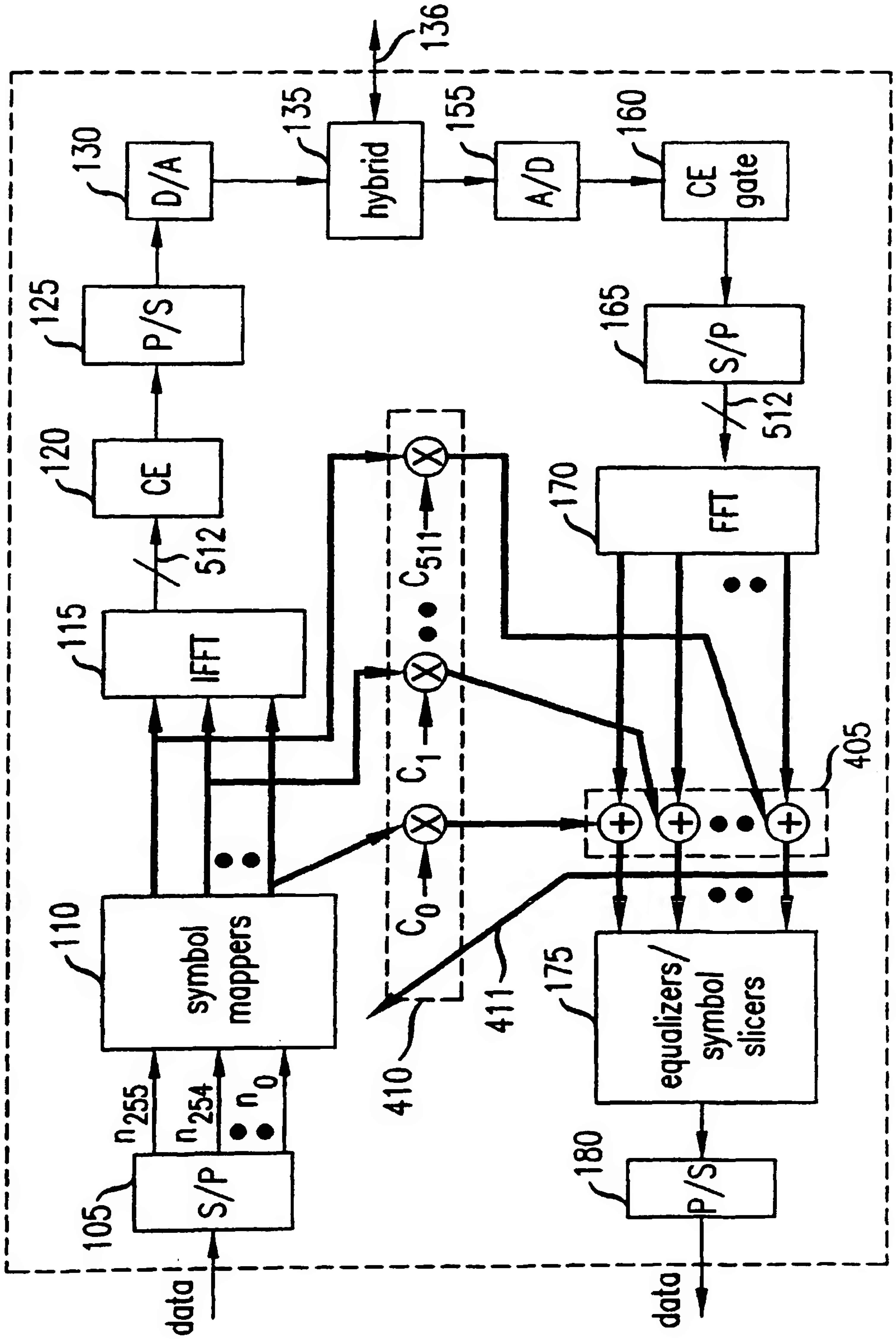

200
250
ADSL
(CO)
twisted pair
ADSL
(CP)

FIG. 14

400


data
S/P
105
n_{255}
n_{254}
n_0
symbol mappers
110
IFFT
115
512
CE
120
P/S
125
D/A
130
hybrid
135
136
A/D
155
CE gate
160
S/P
165
512
FFT
170
C_0
C_1
C_{511}
410
411
405
equalizers/ symbol slicers
175
P/S
180
data